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AN AUDITORY-VISUAL INTERACTION MODEL FOR MONITORING ARMY MATERI--ETC(U)

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Technical Memorandum 37-76

AN AUDITORY-VISUAL INTERACTION MODEL FOR MONITORING ARMY MATERIEL/INFORMATION DISPLAYS

Lynn C. Oatman

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U. S. ARMY HUMAN ENGINEERING LABORATORY

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In many military operations, such as in command or air-traffic-control centers, great quantities of information are displayed to the operators simultaneously. ~~The present~~ This paper discusses the process of selective attention. It reviews recent models of information processing, and suggests a model of auditory-visual interactions which describes the processes that might underlie selective attention. The model suggests that a central processor allocates capacity for processing important sensory messages in preference to others. The model suggests how the human operator can routinely operate in an environment where many signals compete for attention, where time available for dealing with each signal is limited and where the required precision of analysis changes continuously.

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AN AUDITORY-VISUAL INTERACTION MODEL FOR MONITORING ARMY MATERIEL/INFORMATION DISPLAYS

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December 1976

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CONTENTS

AN AUDITORY-VISUAL INTERACTION MODEL FOR MONITORING ARMY MATERIEL/INFORMATION DISPLAYS

INTRODUCTION

The designers of modern weapon systems often produce man-machine systems where the human operator must operate controls in response to information obtained through visual and auditory channels. In many military situations the human operator must simultaneously monitor a visual display and listen to one or more incoming messages. For example, the observer who must track missiles or aircraft on a complex CRT display must also communicate with his firing battery (Figure 1).

During the last few years the U.S. Army Human Engineering Laboratory (Monjan & Annau, 1971) has been studying some of the problems related to the acquisition of auditory and visual information from auditory-visual displays. The project has led to exploring some of the sensory interactions that occur when auditory and visual information are presented simultaneously. Questions about the human capability to process simultaneous auditory and visual information have become an important area of human-performance theory in recent decades. Classical research has indicated that the human operator is easily overloaded by simultaneously presented information. The limitations in the human operator's capacity to receive, process, store, and act upon information have resulted in the influential single-channel theory of information processing.

Broadbent (1958) described a single-channel theory of information processing where a peripheral filter protected a central mechanism with limited capacity from being overloaded by simultaneous stimulus inputs. The filter blocked out all but one selected input. This theory, although it had considerable success, failed to account for a number of findings. The most serious objections to Broadbent's theory arose from Treisman's (1960) observations which indicated that, under some circumstances, subjects do respond to the content of the rejected channel. The present model proposes that the filter merely attenuates input from rejected channels, rather than blocking it altogther. In other words, the central nervous system operates like a biological filter—attenuating information from one sensory system when it is necessary to pay attention to information coming in from another sensory system. It is necessary that an individual be able to filter out irrelevant information, if he is to continue functioning in a integrated manner. When the sensory processor is overloaded, the human operator can become confused, disoriented, and unable to perform efficiently. Therefore it is important that one understand this filtering process, especially in the design of military equipment, where human operators must acquire and act upon information received simultaneously through the auditory and visual channels.

The present paper is concerned with the process of selective attention which causes auditory-visual interactions. In particular, it is concerned with a model of those mechanisms which enable organisms to respond selectively to important features of their environments, while ignoring features which are of little or no importance. Attention is a word that can be applied to a large number of psychological processes. One important distinction that must be made is between attention to anything at all and attention to one specific thing, rather than to another. The former can be thought of as arousal, the later as selective attention proper. In selective attention the human operator is continually being faced with a mass of stimulation and can only assimilate a limited amount at a given instant. Consequently, he must choose between stimuli.

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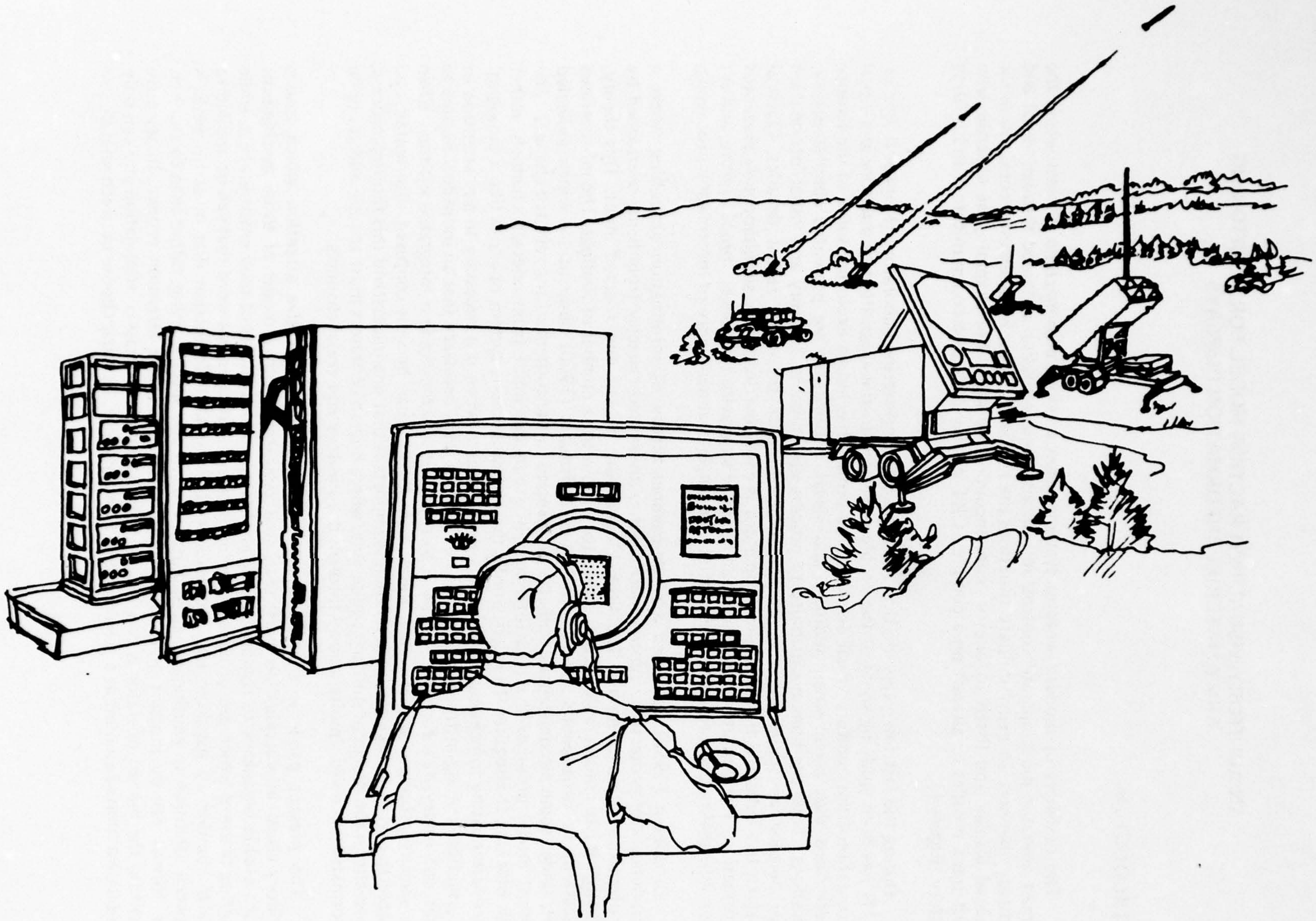

Figure 1. The human operator is visually tracking several objects on his radar screen and is also communicating with the firing battery through his earphones.

The purpose of this paper is to consider a single model of the processes that might conceivably underlie selective attention. The model is doubtlessly too simple to account fully for the physiological mechanisms in selective attention; however, it provides the basis for a number of readily testable predictions. Hopefully, an attempt to test these predictions may provide some of the insight necessary to replace this model with others that have more predictive power.

RECENT MODELS OF INFORMATION PROCESSING

The first major theory of information processing, and certainly the most influencial one, was proposed by Broadbent (1958). Broadbent suggested an information-processing model which relies heavily on the concept of selective attention. The most impressive demonstrations of selective attention have come to us from Cherry (1953), who originally showed how little information one retains from one message while simultaneously shadowing (i.e., repeating back word-by-word) another message. Cherry played two simultaneous auditory messages to subjects, one message to each ear. The subjects were required to shadow one of the messages. After the shadowing was completed, subjects were questioned about the content of the unattended message. Under these circumstances it was virtually impossible to retain any information about the verbal content of the unattended channel. A subject who is not specifically instructed to detect some feature of the rejected message apparently knows virtually nothing about that message, not even the language in which it was spoken. Even when the subject is instructed to detect specific events on the rejected channel, he does very poorly, as Treisman has demonstrated (1967, 1969). Broadbent viewed the nervous system as a single communication channel which has a limited capacity to transmit information. He suggested that a filter (the mechanism of attention) operates on sensory input channels in order to avoid overloading the limited-capacity channel. The filter selects one input and blocks out the rest, making its selection on the basis of physical cues such as spacial location, voice, intensity, etc. Broadbent (Figure 2) envisaged a system in which auditory and visual inputs converge onto a switch which can select any one incoming message, while holding messages from other inputs in a short-term store preceding the switch. Following the switch is a limited-capacity channel. Once an input channel has been selected, the transmitted information has access to long-term memory and response mechanisms.

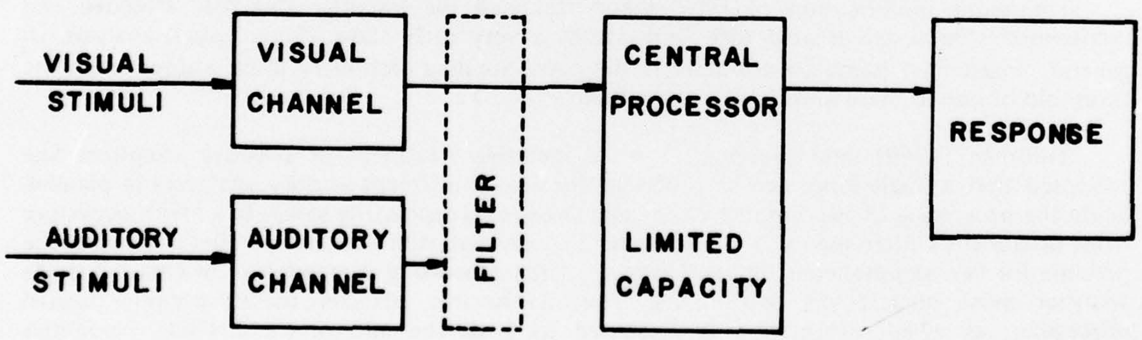

Figure 2. A single-channel model of information processing described by Broadbent (1958), where a peripheral filter protects a central mechanism of limited capacity from overload by simultaneous stimulus inputs. The filter blocks out all but one selected input.

According to Broadbent's model, the filter (attention) is only capable of processing information from one channel at a time. To deal with simultaneous multiple inputs, the filter is switched from channel to channel, sampling information from each channel sequentially for a brief, finite interval. To counteract the effects of a limited central-processing mechanism, information received from one modality can be held briefly in a short-term store while information arriving from another modality is processed.

Broadbent's model, although it had considerable success, fails to account for a number of findings. The most serious objections to Broadbent's theory arose from Treisman's (1960) observations, which indicated that, under some circumstances, subjects do respond to the content of the rejected channel. In this experiment, Treisman (1960) presented two passages of prose, one in each ear, and instructed her subjects to shadow (i.e., repeat back) the message in a particular ear. Halfway through, the messages were switched so that the message the subjects had been shadowing was changed to the wrong ear. It was found that subjects would repeat one or two words from the wrong ear before reverting back to shadowing the correct ear. These results suggest that subjects can respond to words in a rejected channel. Similarly, Moray (1959) has shown that when the listener's own name was inserted into the rejected message, it was recognized on approximately 30% of the trials. Subjects also identified other types of messages presented to the rejected ear, including a pure tone, a man's voice later switched to that of a woman, speech and foreign language, and reversed speech. Clearly, this could not happen if rejected messages were not receiving some perceptual analysis. Results such as these led Treisman (1960) to propose that the filter merely attenuates input from rejected channels, rather than blocking it altogether.

According to Treisman (1960), information flows into the organism through a number of parallel channels. The messages reach some part of the nervous system where they are analyzed for physical properties, such as loudness, pitch, position, color, brightness, etc. As well as extracting such physical characteristics, the mechanism can attentuate the signal at the output of these analyzers, and it is in this way that the filter operates. Treisman (1960) suggested that a sensory message activates hypothetical "dictionary units" in memory. Each unit has a threshold which must be exceeded before perception can occur. When the context makes a word probable, its threshold is lowered temporarily, while thresholds for highly significant stimuli, such as one's name, are permanently lowered.

Treisman's modification of filter theory retained the essential idea that attended and unattended stimuli are treated differently from a very early stage of perceptual analysis. In general, unattended items do not activate the corresponding dictionary units, except when the threshold of one of these units is exceptionally low.

Treisman (1969) later presented a more inclusive treatment of selective attention. She proposed that a single input can be processed by several different sensory analyzers in parallel, while the processing of two inputs by the same analyzer is necessarily serial. In a major departure from Broadbent's filter theory, she concluded that divided attention and parallel processing are possible for two simultaneous inputs. However, serial processing is mandatory whenever a single analyzer must operate on two inputs. Thus Treisman's analyzer theory permits parallel processing, as when information is presented to both the auditory and visual modalities simultaneously.

In the well-known work of the physiologist, Hernández-Peón, a filter mechanism was implied in the structure and functioning of the nervous system. Hernández-Peón, Scherrer, and Jouvet (1956) and Hernández-Peón (1966) recorded auditory evoked potentials from the dorsal cochlear nucleus in chronically implanted unanesthetized cats. When the cat was given some

stimulus besides auditory clicks—such as visual (two mice in a closed bottle), olfactory (fish odors), or pain (shock delivered to the forepaw)—the amplitude of the auditory evoked response was attenuated markedly. These observations suggested that afferent auditory impulses were blocked at a peripheral level of the auditory pathway by some central inhibitory mechanism, which was assumed to be the mid-brain reticular formation. Hernández-Peón (1961) suggested that the reticular formation in the brain stem resembles a "high command," and that it receives all kinds of information from the external and internal environment. In turn, this region of polysensory convergence has feedback circuits which filter all the sensory impulses as they enter the central nervous system. In this way, a filtering mechanism is closely linked to the mechanisms that select which information will be amplified at higher levels of the brain. Indeed, such a mechanism would be in concordance with the single-channel model Broadbent generated from behavioral data.

As plausible as Hernández-Peón's peripheral-filtering model appears, certain methodological problems arise. The attenuation of the auditory evoked potentials in cochlear nucleus mentioned earlier (Hernández-Peón et al., 1956) was also found to occur because of changes in the cat's position in the sound field (Marsh, Worden, and Hicks, 1962). Additional influences on auditory input have been shown (Baust and Berlucchi, 1964) to involve the middle-ear muscle reflex, as well as head movement (Starr, 1964). However, the sound input and the middle-ear muscle reflex were controlled in a subsequent experiment by Oatman (1971). In this experiment, the changes in auditory evoked potentials were shown not to be due to peripheral non-neural factors, but to centrifugal neural mechanisms.

Although Broadbent, Treisman, and Hernández-Peón retained the filter concept in their models of information processing, other authors have questioned the necessity of a filter mechanism. Deutsch and Deutsch (1963) have argued that an adequate filter requires discriminatory capacities as complex as those used in normal perception. Consequently, it has been suggested that selection occurs only after all sensory input has been completely analyzed. Therefore, Deutsch and Deutsch (1963) (Figure 3) proposed that it was unnecessary to postulate a filter mechanism at all, since a message receives the same perceptual analysis whether or not attention is paid to it. They postulated central structures, equivalent to Treisman's dictionary units, but suggested that attention does not affect the degree to which sensory stimulation activates these structures. The dictionary unit fires more strongly for more important stimuli, not necessarily because it is stimulated more strongly. The importance weighting is a function of past experience. Only if another unit begins to fire more strongly will a first unit be displaced; otherwise it will continue to occupy the output mechanism until it is no longer stimulated by the input signal. In addition, the general level of arousal limits the dictionary output's access to further stages of the mechanism. If the general level of arousal is low, only the most important signals will be able to trigger the output mechanism. As the level of arousal increases, more and more signals will be able to get access to the system's response site.

Broadbent's theory asserts that it is simply impossible to divide attention among several stimuli, since attention can only be directed to one channel at a time. Deutsch and Deutsch, however, implied that it should be easy to detect an important signal, whether or not the observer is attending to the channel on which the signal is presented. Deutsch and Deutsch (1963) imply that all stimuli reaching the senses are fully analyzed for meaning, in order that those of importance may receive response. However, it is difficult to understand why the rejected items, once fully analyzed, are so completely lost that no recall is possible in subsequent learning of material which has struck the ear but not received attention (Moray, 1959).

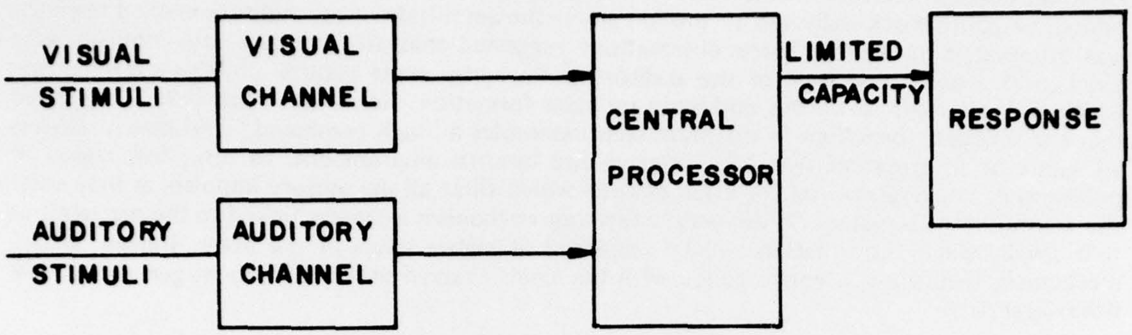

Figure 3. An alternative to Broadbent's filter theory was the response-selection model described by Deutsch and Deutsch (1963), where all sensory messages receive the same perceptual and discriminatory processing in the central processor. However, access from the central processor to the response mechanism is limited.

Other alternatives to filter-attenuation theory have been proposed by Neisser (1967, 1969). According to Neisser's theory, selective attention is an active process of analysis by synthesis, or reconstruction of an internal representation of the input. The process transforms sensory information into a coded form which may be used by perceptual and associative mechanisms. The process is serial, so it can process only a limited amount of input at one time. Here irrelevant, unattended messages are neither filtered out nor attentuated; they merely fail to enjoy the benefits of analysis by synthesis. Neisser indicates that he can account for the selective-attention data without using a filter mechanism. His theory may adequately explain the direction of attention, but it does not adequately explain the selectiveness of attention. With simultaneous auditory and visual input, it is not clear why there is no analysis of the second input during the analysis of the first. There is an implication that this is because the analysis circuits are "busy". However, it seems that there is nothing to prevent additional inputs from impinging on the analysis mechanism, thereby disrupting the analysis of the first input. If the analysis mechanism has a limited capacity for processing information, there is nothing to prevent other inputs from overloading it. It is apparent that, although Neisser objected to the idea of a filter, the selection of messages for analysis is undistinguishable from a filtering process. Unless one postulates a mechanism which prevents the analysis of one input during the analysis of another, it appears that the rejected input should produce an information overload and cause more interference than appears to be the case. Neisser has assumed that a serial process which can accept only one input at a time is also necessarily a mechanism that prevents the analysis of one input while another is being analyzed. This assumption appears to constitute a filter mechanism.

SINGLE-CHANNEL AUDITORY-VISUAL INFORMATION-PROCESSING MODEL

The model being proposed deals with the process of selective attention which results in auditory-visual interactions. This model differs from previous models in that it is concerned with the physiological processes that might conceivably underlie a filter mechanism. The general outline of the model owes much to Treisman's formulation, but it can be thought of as making the filter's action more explicit. The model postulates that attention is, in fact, a two-stage process: first, there is filtering on the basis of the channel characteristics, which results in the attenuation of incoming rejected messages; and second, there is further filtering by the threshold settings of the feature analyzers. The fundamental assumption of the model is that all incoming messages are funneled through a single-channel processor which can deal with only one message at a time. When simultaneous auditory and visual signals reach the senses, they are held in parallel in a buffer store for a limited time. During this time some information proceeds to a central processor mechanism, which has limited capacity and operates serially. When several messages occur simultaneously, the information in some messages may be lost because others are being processed. The loss of information during the perception of the stimulus accounts for the impairment of performance when a human operator attempts to do two or more tasks at the same time (Oatman, 1975).

Auditory and visual information flow into the human operator through a number of parallel channels. It is assumed that incoming signals are initially analyzed into separate perceptual channels, each of which transmits information about a particular feature or parameter, such as loudness, pitch, position, color, brightness, etc. The information resulting from this analysis is available to conscious perception so the operator can report it. During signal analysis, some source of interference limits the total amount of information that can be handled.

Target selection depends on using one or more of a set of these critical features, i.e., color, pitch, loudness, etc. The tasks related to these features would include searches for objects, or vigilance tasks. Whether a subject attends to targets selectively may depend upon the particular combination of defining stimuli. Differences between targets may depend solely on the basis of input differences, or solely on the basis of analyzer differences, or on a combination of the two. Whether the laws of selective attention for these compounds can be predicted from the laws of selective attention of the elements is not yet known for the human data. Kahneman (1973) has argued that selective attention occurs after unit formation in the information-processing sequence. Perhaps the most interesting aspects of attention remain to be explored and may be in the realm of attention to objects and events, rather than to dimensions.

As well as extracting particular features of the stimulus, the central processor can act to attenuate the signal input, and this is the way the filter operates. Much recent research into the physiology of perception suggests that both the reticular formation and the direct or classical pathways, which represent the physiological analogues of the central processor, are involved in normal perception. When an organism is engaged in attentive behavior, a selective process occurs within the central nervous system, where relevant stimuli are perceived while irrelevant stimuli are rejected. Some stimuli are rejected at very early stages in the afferent pathways, and sensory information is transmitted to the cortical areas only after it has been subjected to "filtering" at the peripheral level. Worden (1966) discussed two neurophysiological systems which could be responsible for filtering auditory information at the peripheral level. One system, a reticular feedback system, involves the regulation of auditory stimuli through middle-ear-muscle contractions. The other system, an extra-reticular feedback system, involves the regulation of auditory stimuli through the action of the olivocochlear bundle (OCB). It is believed that the OCB inhibits auditory stimuli to the central nervous system at the peripheral level (Oatman, 1971). These two inhibitory systems are thought to be the physiological mechanisms responsible

for the filtering process that controls auditory input to the central nervous system. Oatman (1971, 1976) also showed that when an organism is attentive to meaningful visual information, non-meaningful (auditory) information is attenuated. Therefore, during attention to visual information, the central processor activates an inhibition system which attenuates other sensory inputs (Figure 4).

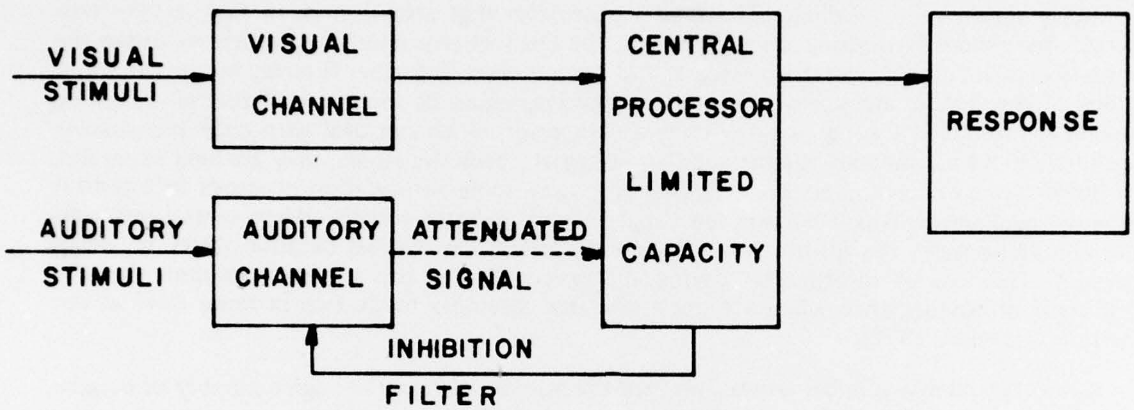

Figure 4. A single-channel model of information processing described by Oatman. A peripheral filter attenuates some sensory information, which protects a central processor of limited capacity from overload by simultaneous stimuli. The central processor activates an inhibitory system which attenuates sensory information at the peripheral-receptor level.

The attenuated messages and the attended message pass into the central processor. The feature analyzers and the central processor have different thresholds, and their thresholds are variable. Some analyzers have thresholds which are always lower than most analyzers. For example, the feature analyzers which respond to the occurrence of biologically or emotionally significant signals have permanently lowered thresholds. The feature analyzers which respond to one's own name have permanently lowered thresholds. Therefore, even if such a signal has arrived along the line whose signal strength has been attenuated by the filter, it will trigger its feature analyzer.

The overall capacity of the central processor is limited. However, the brain can divide its capacity, its processing networks, allocating them in different ways and using them for any of several tasks. For example, even though messages in the unattended channel are attenuated, the central processor could allocate a small proportion of the available sampling capacity to the unattended channel. The capacity allocated would be sufficient to permit gross discrimination in the channel. A scheme like this would have the attractive property of preserving most of the discrimination capacity for the channels of primary interest while, at the same time, allowing for the possibility of detecting signals on unattended channels provided the signals are important or have permanently lowered thresholds. Processor capacity is used less efficiently for discrimination when it must be shared between two tasks, but it costs no more to share among four than to share among two (Taylor, Lindsay, and Forbes, 1967). Also, sharing within the modality is as difficult as sharing between sensory modalities.

Therefore the human operator is a time-sharing system, at least in the limited sense of being able to deal somewhat with several inputs at once. As in any time-sharing system, there must be a control unit in the central nervous system, which keeps track of the storage and capacity requirements of various simultaneous inputs, and allocates capacity to a sensible order of priorities. The limiting case of time-sharing is that of an operator who works at a task, but is simultaneously exposed to *irrelevant and attention-demanding* stimuli. Then attention is allocated optimally if the operator gives all of his attention to the task and ignores the irrelevant stimulation. Kahneman (1970) has pointed out that the mean level of performance under distraction stress is quite stable, although the variance increases, both within and between individuals. He further indicates that the relative stability of performance under distraction shows that information-processing capacity is properly allocated to the main task, but this stability is achieved at a distinct cost. In a noisy input situation, more processor capacity will be allocated to the reception task, so that an optimal signal-detection network may be organized. Hockey (1969) has pointed out that long exposures to loud noises induce a significant increase in the level of arousal, with a secondary effect on the level of performance in accordance with the familiar Yerkes-Dodson law. Performance may improve on an easy task (McGrath, 1963), or deteriorate when the task is complex (Broadbent, 1958). The evidence suggests that a distractor is more likely to obtain processing capacity when the primary task is easy. The single-channel hypothesis, in its most rudimentary form, predicts a simple all-or-none response, where the human operator should be able to deal with only one signal at a time and performance on all other signals should drop to chance. The fact that this result seldom occurs in attention studies has prompted the use of increasingly complex tasks, in an attempt to examine the human operator's capability of alternating his attention among the different signals. There is ample evidence that the human operator cannot respond to simultaneously presented stimuli as efficiently as he can respond to the same stimuli when they are presented alone (Oatman, 1975). To deal with simultaneous multiple inputs, attention is switched from channel to channel, sampling information from each channel sequentially for brief finite intervals. Basically, we follow Kristofferson's (1967) notion of attention, where the central nervous system has a gating *mechanism* that controls the flow of information from the sensory channels into a central data processor. The gating mechanism is not considered to be all-or-none; rather, it attenuates information from the sensory displays. However, the central processor is only open to one channel at any instant. Attenuated input from unattended channels is processed along with stimulation from attended channels. However, unattended input is effectively weaker, so it is less likely to receive extensive analysis. Although processing of two channels "at once" in such cases would seem to be at variance with a single-channel assumption, this is not the case. For example, a dual-trace oscilloscope is a device which is capable of displaying two waveforms at the same time. However, the display's rudimentary form of processing is accomplished by alternating rapidly between input channels. Thus, at a microscopic level, only one signal is processed at a time. At a more macroscopic level, the effect is of simultaneous processing. We assume, as Kristofferson (1967) did, that switching from one channel to the other is practically instantaneous. If two inputs with long durations occur simultaneously, the human operator can switch attention from one to the other and process both inputs at a leisurely manner without losing any of the available information. If, on the other hand, two simultaneous inputs are very short, there may not be sufficient time to handle the information from both channels in succession. Thus simultaneous tasks impair the human operator's performance more if their

inputs are short than if they are long (Tulving and Lindsay, 1967). Therefore the human operator's performance is reduced, not because he completely failed to monitor the auditory and visual channels, but because a given channel is monitored for only part of the time when the signal is being presented. Increasing the number of channels reduces the time available for sampling the information in each channel.

SELECTIVE ATTENTION AND AROUSAL

Conceptually, selective attention and arousal can be differentiated, although this distinction is not often made experimentally. Attention refers to some very selective behavioral interaction with environmental stimuli, whereas arousal pertains to some aspect of the state of wakefulness. In order to be attentive and behave very selectively when presented with a barrage of stimuli, the human operator must be aroused or awake. The idea that the general state of organismic arousal is inextricably tied to stimulus selection, has blurred the distinction between arousal and selective attention. Wakefulness is not a necessary condition for attention, as demonstrations of stimulus selection during sleep have shown. An organism can be asleep and attentive (Oswald, Taylor and Treisman, 1960) or asleep and inattentive, awake and attentive, or awake and inattentive (day dreaming). Therefore, even within the waking state, arousal and attention can be differentiated empirically (Weinberger and Lindsley, 1965). Although arousal and attention interact, neither is a sufficient or necessary condition for the other. This suggests that neural substrates of arousal level ought to be different from those underlying selective attention.

During the past two decades, the thinking about the neural substrates of attention has been dominated by important insights into the role of the ascending reticular activating system (ARAS) in modulating arousal. Since the pioneer observations of Moruzzi and Magoun (1949), it has been known that arousal is elicited by high-frequency electrical stimulation of a region located in the core of the brain stem, extending from the medulla up to the ventromedial part of the thalamus. Magoun (1952) termed this region the ascending reticular activating system (ARAS). Magoun and his colleagues demonstrated the ARAS plays a critical role in the EEG and in behavioral manifestations of arousal. Subsequently, the notion that the "nonspecific" thalamic nuclei, which are the cerebral extensions of the brain-stem reticular formation, control focal and phasic shifts in the cortical activation related to selective attention has gained wide support (Jasper, 1960).

For a number of years, Hernández-Peón (1961) and his co-workers dominated the field with their experimental studies. They used two basic experimental procedures. The first procedure recorded sensory evoked potentials to monotonously repeated stimuli. It was presumed that the animal would attend to the stimuli, and then, when the stimuli were found to be unimportant, ignore them. The evoked potentials' amplitudes were assumed to vary with the fluctuations in attention. The second procedure was to deliver repetitive stimuli before, during, and after presentation of a highly important stimulus in another sensory modality. It was assumed that the repeated stimuli were not attended to while the distracting stimulus was presented. In both experimental procedures, it was reported that evoked potentials recorded at the first nucleus of the respective sensory pathway were suppressed in amplitude when the stimuli were presumed to be unattended. These findings led to the hypothesis of afferent neuronal inhibition, which postulated that the reticular formation has a centrifugal inhibitory action on the specific sensory nucleus when a perceptual or behavioral response in that modality is suppressed.

The reticular formation has been assumed to have an excitatory effect on cortical mechanisms. Some question concerning this hypothesis has persisted, due to the often-contradictory results reported for arousal's effect on the amplitude of cortical evoked

potentials. This question has been clarified somewhat by recognition that the reticular formation might affect the thalamus and cortex differently (Steriade, 1970). Steriade has shown that, during arousal, there is a facilitation of thalamic excitability, but a state of tonic arousal is accompanied by a reduction in the responsiveness of the cortex. He also pointed out that the temporal properties of the stimulus are an important factor in how arousal affects cortical evoked potentials. When a visual evoked potential is produced by a single electrical shock delivered to the optic nerve, arousal increases the amplitude of the evoked potential (Bremer and Stoupel, 1959; Walley and Urschel, 1972). On the other hand, the amplitudes of evoked potentials produced by a diffuse photic stimulus are suppressed under the same conditions, and in the same animals (Walley and Urschel, 1972). Walley and Urschel (1972) have argued that these results may be explained by assuming that arousal facilitates cortical recurrent inhibition. It is assumed that the reticular formation will facilitate cortical recurrent inhibition. The strongest support for this assumption is provided by the studies of changes in the cortical excitability cycles during arousal. During attention, there is generally an increase, which facilitates recurrent inhibition in the cortex.

The above evidence has strengthened the hypothesis that increasing the arousal narrows attention (Tolman, 1948) or the range of cue utilization (Easterbrook, 1959). The fundamental law that relates the human operator's performance to arousal is the Yerkes-Dodson law, which states that the quality of performance on any task is an inverted U-shaped function of arousal. The range over which performance improves with increasing arousal varies with task complexity (Yerkes and Dodson, 1908). Easterbrook (1959) has shown how the inverted U-shaped function relates to arousal and performance. On complex tasks which require the use of a number of different cues, high arousal can be detrimental to performance if attention becomes so narrow that it impairs the use of all of the relevant cues. According to this idea, increases in arousal produce a narrowing of attention. In other words, if we view moderate arousal as leading to a narrowing of attention, the human operator's performance is fine. One would expect that as arousal increases, performance first improves (as irrelevant cues are excluded), and then gets worse (as relevant cues are also excluded). This is consistant with a large body of experimental literature. If we assume that one of arousal's primary effects is narrowing the width of the attentional beam, then we might expect that, at extremely high levels of arousal, the attentional field may become so narrow that the operator cannot maintain any stable orientation toward the environment. Variations of arousal not only cause a corresponding narrowing of attention, but variations of arousal may also affect the policy for allocating attention to different activities.

CAN ATTENTION BE FOCUSED?

The human operator's ability to concentrate on a single stimulus is a manifestation of selective attention. In the early studies of focused attention, the subject's attention was focused on his mental activities, but later studies of selection typically deal with the ability to select a relevant stimulus in the presence of others. Many studies, such as Cherry (1953), have used the shadowing task, in which the listener follows a message by repeating every word, and attempts to ignore other messages to which he is simultaneously exposed. Cherry (1953) established that subjects are always aware the rejected message is being presented to the unattended ear, but know virtually nothing about it when questioned subsequently. They also failed to detect the switch to inverted speech on the rejected channel.

Inputs can be selected effectively when they are distinguished by an appropriate cue. This is true both in the shadowing experiments and in other tasks. In tachistoscopic presentations of complex arrays, the human operator can be set to select items in a particular row (Sperling,

1960) or items of a particular color (von Wright, 1968, 1970), and he performs as well as if the irrelevant material had not been present. Monitoring an auditory message for critical items is almost as effective when a competing message is presented to the other ear as without that message (Moray and O'Brien, 1967). Eriksen and Hoffman (1972) have reported a series of experiments which demonstrated attentional focusing mechanisms. They found that subjects perform better when they are given foreknowledge of where the target will appear. On each trial a single letter was presented at one of four locations on the circumference of an imaginary circle surrounding the fixation point. Just before the letter was displayed an indicator appeared near the spacial location that the letter would occupy. The warning interval varied from 0 to 150 msec. Interestingly, the latency to identify the letter was up to 40 msec. faster with the precue than when the indicator appeared simultaneously with the target letter. This finding suggests that the indicator facilitated recognition by giving the human operators the opportunity to focus their attention to the proper location in the display.

Forbes et al. (1967) performed another experiment which showed that precuing subjects to attend to one of four presented dimensions produces a clear superiority of performance on that dimension, as compared to the situation in which they were required to process all four dimensions. These effects show that precuing facilitates performance relative both to a 0-delay post-stimulus cue and to post-stimulus cues of greater delays. If the subject is given an information overload, the amount of information per dimension is reduced. Precuing, on the other hand, improves transmission on the relevant dimension. These facts seem to argue that the facilitating effect of precuing is a focused selective-attention effect operating on perceptual mechanisms, rather than on post-perceptual mechanisms such as storage or rehearsal. If the effect were purely post-perceptual, one would expect the 0-delay cuing to be superior to longer cuing effects.

In another study, Zelnicker (1971) provides evidence for the role of capacity demands in focused attention. Three groups of four auditory digits were presented in rapid succession. There were two experimental conditions, which may be labeled Easy and Hard. In the Easy condition the subjects repeated the first group of digits twice, synchronizing his responses with the second and third groups heard on the tape. In the Hard condition he repeated the first group while hearing the second, and he repeated the second while hearing the third. In both conditions the subject was also exposed to a playback of his own voice, which was delayed by 0.2 seconds. Such delayed auditory feedback causes stuttering. The amount of stuttering was compared for the first group of digits that the subject reported. There was less stuttering in the Hard condition. Attempting to listen to the second group of digits while speaking, made it easier to ignore the delayed auditory feedback. Since delayed auditory feedback is an extremely unpleasant experience, the subjects must have been motivated to ignore it under both experimental conditions. It is consistent with the notion of limited capacity that they were more successful when engaged in the demanding task.

The evidence reviewed above is generally consistent with predictions from the model. The model assumes that a filter sorts simultaneous stimuli by physical characteristics, such as position, color, etc. Further perceptual analyses are applied only to stimuli which share the property that defines the relevant channel. The biological filter rejects other stimuli. Irrelevant sensory information is stored momentarily, but then it is permanently lost unless the filter shifts and allows it to be processed. Thus the material presented to an irrelevant channel is not analyzed perceptually, beyond a few tests on physical features. Even in the presence of irrelevant stimulation, a relevant input can be processed effectively when attention is focused on it. However, focusing attention on one message does not completely prevent the processing of stimuli on irrelevant channels.

CAN ATTENTION BE DIVIDED?

One assumption from the model that has been central in the analysis of selective attention in humans has been that of a limitation on the system's processing capacity. It is this notion that has led to the hypothesis that the human operator functions as a single-channel, limited-capacity system. Once capacity is reached, additional information can be transmitted only be adding time. Sufficient time will allow the human operator to switch attention between different sources of information. If, however, time is constrained and the human operator is required to divide his attention between two or more sources, he will do so with less than optimal performance on each.

In order to divide attention successfully, the human operator must be able to simultaneously process information from each of two or more sources as well as when each source is presented alone. This task is different from those monitoring tasks where only one signal is actually presented and one response required at any one time. Various experiments have examined performance when subjects must make several discriminations on each trial. Most of these studies show decrements in performance, but a few have shown successful division of attention.

A number of experiments point to the conclusion that a performance decrement occurs when the human operator must perform several discriminations on each trial. The work of Lindsay, Taylor, and Forbes (Forbes, Taylor, and Lindsay, 1967; Lindsay, 1970; Lindsay, Taylor, and Forbes, 1968) is illustrative. These investigators have examined the information process and capacity of the human operator in absolute-judgement and two-alternative forced-choice tasks. In these studies, the subject was to discriminate between two values in each of four possible dimensions (2 visual and 2 auditory). The two visual dimensions were vertical and horizontal displacements of a small spot on a screen. The auditory values were two frequencies and two loudnesses of a pure tone. Various combinations of 1, 2 and 4 possible dimensions were tested, and only those dimensions that the human operator was required to process were varied within a series. Thus, if the human operator was required to process vertical displacement and pitch at the same time, horizontal values and loudness values were held constant. The results from one of their studies show that, for short durations, the total amount of information processed is roughly constant as the input varies from one to four dimensions. This general result held for both the discrimination experiment (Lindsay et al., 1968) and for a stimulus-identification experiment (Lindsay, 1970). One of the most important results of their experiments is that, for brief durations, information transmission was nearly constant whether the input was from 1, 2, or 4 dimensions.

Lindsay, Cuddy, and Tulving (1965) and Tulving and Lindsay (1967) had subjects identify the intensity of auditory and visual signals presented both individually and simultaneously. The results indicate that performance under the simultaneous condition was just slightly poorer than in the individual condition, indicating successful division of attention. Even clearer evidence of divided attention was obtained by Moore and Massaro (1973), who had their subjects identify either one or both of the dimensions of loudness and quality (waveform) of a brief test tone. The results showed equal performance in both the divided-attention and directed-attention conditions. The critical differences between the Lindsay et al., and Moore and Massaro studies are not known and will not be known until some experimenter produces both effects within the same design. Moore and Massaro suggested that the different results from Lindsay et al., arise from failing to vary the irrelevant dimensions in these divided-attention conditions.

These papers by Lindsay, Taylor, and Forbes demonstrate that, under some circumstances, the human operator loses information when required to process more than one dimension at a time. The results of these papers are somewhat unusual, because they suggest that these effects are indifferent to the modality or the channel which the human operator is required to process. Other studies have indicated that divided-attention effects depend partly on the nature of the stimulus, and partly on how the human operator is required to divide his attention.

The evidence reviewed above is generally consistent with a modified single-channel model which suggests that the limits to parallel processing in divided attention are set by the overall capacity. There is some overall limit to the capacity of the perceptual system. This can be devoted completely to one difficult task, as in focused attention, or it can be divided between two or more easier ones, but only up to some limiting level (Moray, 1967; Lindsay, 1970).

CONCLUDING REMARKS

Since the human operator has a limited capacity to receive, process, store and act upon information, some kind of selective process within the central nervous system causes relevant sensory information to be perceived, while irrelevant information is rejected. The locus of selective attention has probably been the foremost theoretical question in the past several years of research on attention. The earlier models of selective attention have been concerned with whether the process which allows an organism to process sensory inputs selectively is a peripheral or a central mechanism. While Broadbent's earlier model proposed that there is a peripheral filter, the present model assumes the selective mechanism is a central process with a peripheral site of action. The neurophysiological data presented suggest the centrifugal modulation of information at the peripheral levels. The exact mechanisms involved in selective attention still remain to be elucidated. Although it has been established that there are many centrifugal pathways in the central nervous system, no clear demonstration of their role in attention has been reported. Placing the "attention mechanism" in the reticular formation still remains attractive, although far from unequivocal.

The present model suggests that a central processor allocates capacity for processing certain sensory messages in preference to others. This focusing of attention is very effective in attenuating irrelevant stimuli and keeping irrelevant stimuli from interfering with the primary tasks, but there is evidence that irrelevant stimuli are sometimes processed, at least up to the level of recognition. The present model provides a unifying framework for analyzing various attention mechanisms. It plays a useful role in our initial attempts to understand how the human operator can routinely operate in an environment where many signals compete for attention, where the time available for dealing with each signal is limited, and where the precision of analysis required is continuously changing. One of the present model's distinct predictions is that the effectiveness of selection depends on the ease with which relevant stimuli can be segregated at the periphery, and that the effectiveness of rejecting irrelevant stimuli depends upon the amount of capacity the primary task demands.

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